Xiantang ZHANG, Hongmin ZHOU, Hongli WANG, Kangning GAO

Shandong Provincial Key Laboratory of Civil Engineering Disaster Prevention and Mitigation, Shandong University of Science and Technology

Analysis on Wave Forces Acting on Box Girder of Twin-Decks Offshore Bridge

Abstract. *Based on the practice twin-decks bridge and model test, and considering different deck elevation and the different wave factor, the wave loads of various models were simulated using the 2D numerical wave tank, and compare with the corresponding experimental values and theoretical values. All the wave forces have the tendency to decrease after they reach the maximum with the increase of bridge elevation, and there exists the most dangerous bridge elevation under wave action. The optimum elevation of the bridge deck in this paper is recommended +5.5~+6.0 m.*

Streszczenie. *W artykule analizowano siły działające na skutek ruchu fal na dźwigar mostu morskiego dwupoziomowego. Do symulacji wykorzystano metody numeryczne i określono najbardziej niebezpieczne wyniesienie mostu. (**Analiza sił działających na dźwigar dwupoziomowego mostu morskiego**)*

Keywords: twin-decks bridge; wave loads; numerical wave tank; box girder
Słowa kluczowe: most morski, analiza sił

Introduction

In the bridge engineering crossing a waterway or in ocean, the relationship between the safety of the bridge superstructure which is located or lowers than the splash zone and wave impacts is closer. If the girder elevation of the bridges' superstructure is lower, when high waves through the undersurface of the deck or contact with it in bad sea conditions, except a slowly-varying wave pressure of magnitude under the deck, there is also a impact force of considerable magnitude but of short duration as well as the wave crest contact with the deck, which will lead to the instability of the whole superstructure or the local failure of the structure. Besides, it's also an enormous threaten for the wave negative pressure forces to the durability of the concrete structure under the deck when the waves leave the undersurface of the superstructure. In recent two decade, the study on the impact loads have more and more attentions in seashore and offshore engineering designs and have formed a new subject [1-7], whereas there is few literatures for the application research on the bridge structure.

The mechanism of the wave impact processes is extremely complex, the factors referred to involving the strong nonlinearity of the wave, transient effect, fluid viscosity, turbulence, hydrosphere mixing and so on. It's still one of the difficult subjects that have no solutions in the coastal engineering field. The research work of impact forces for waves on structures in splash zone at home and abroad gives priority to the experimental research and numerical simulation [8-10]. The definition of the impulse forces for the mostly practical offshore engineering structure design is usually adopted the empirical equation based on a large number of experiments [11] or the physical model tests that aim at specific projects [12].

We present and discuss the results of an experimental, theoretical calculation and numerical simulation study of the interaction between a free surface wave and twin bridge girders. The latter is modeled as a practical cross more suitable for the basic understanding of the mechanisms governing the phenomenon [10]. The practical engineering is the coastal bridge of one bank protection engineering of the coastal road.

Physical test and research content

The bank protection engineering of the coastal road stretches for 10 km, it locates in tropical storm area, and the sea conditions are adverse and complex. The design standard is high and the project scale and investment is large. The road is made up of coastal bridge, land road, non maneuvering revetment driveway and a full line of landscape engineering. Construction requires that the coastal bridge should be coastal highway twin-decks and the two bridges are not far from each other [13]. Different from bridges on land, the bridge will be under great wave lift and impact because of the low bridge elevation.

Test section

Bridge elevation (BE) are +5.5 m, +6.0 m, +6.5 m, +7.0 m, elevation of sea bed (SBE) are -4.0 m and -10.0 m. The distance from the revetment outside to the centerline of the two bridges is 19.5 m [3], the distance between the two bridges is 2.0 m. Elevation of the revetment front line is +5.5 m, bottom elevation is -2.0 m, the shore protection is a curved wave wall, the cross section of the bridge is shown in Fig.1 (a), The scale of the section and measuring points are shown in Fig. 1(b) [3, 5].

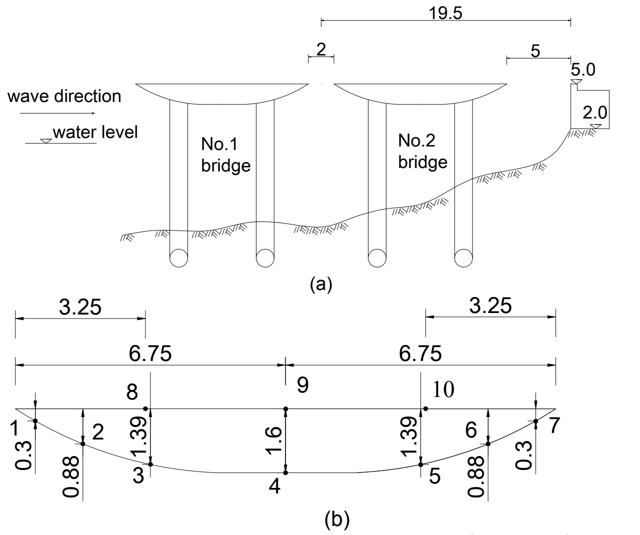


Fig. 1. (a) Bridge cross-section diagram (b) Section of bridge superstructure indicating example locations of pressure transducers imbedded in the model (m)

Wave conditions

Extreme high levels: +4.33 m (return period: 50a, the elevation of Yellow Sea in 1956). The design high water level: +3.16 m. The designed wave parameters are shown in Table 1.

Table 1. The designed wave parameters (return period, 50a) [5]

Water level	$H_{1\%}$ [m]	$H_{4\%}$ [m]	$H_{5\%}$ [m]	$H_{13\%}$ [m]	H_m [m]	T [s]	L [m]
Extreme high water levels +4.33 m	3.58	3.06	2.96	2.50	1.60	5.6	45.72
	5.12	4.45	4.32	3.70	2.46	9.7	97.2
The design high water level +3.16 m	3.44	2.94	2.85	2.42	1.57	5.6	44.82
	5.04	4.36	4.24	3.64	2.40	9.7	93.34

Considering different bridge elevation, elevation of sea bed, different spacing between the two bridges and the influence of the revetment, we can determine the wave force on bridge girder and pile under designed wave action and make observation of the wave level of the bridge and the revetment. In the research, we mainly used irregular wave, moreover the regular wave and irregular wave are compared, and JONSWAP spectrum is used in the imitation of irregular wave [5, 12].

Calculation of wave forces on the bridge

The wave uplift forces on the bridge

According to the fluid mechanics theory, theoretical answer of shallow water wave with little amplitude above the static water can be reached.The maximum uplift force on each linear meter of the deck is [3, 11].

(1) $$F_{zo} = \frac{1}{2}\gamma Hl\sqrt{1+3\delta^2/(1+\delta^2)}$$

where: $\delta=\pi l/L$, H – incident wave height, L – wavelength, l– the length of the deck in the direction of wave propagation, γ – the gravity of water.

Actual measured pressure process line of the model test indicates that, in addition to the static pressure under the deck, whose strength changes slowly, there is also impact pressure that lasts a very short time when the crest is access to the deck. Causes for impact pressure can be interpreted as the sudden changes of vertical wave momentum when the crest is access to the deck.According to the results of several different model tests, it is considered that the maximum impact pressure should be $P_{\mathrm{imax}}\le 2\gamma H$.

In engineering design, it needs to know the total uplift force F_{zo} at the bottom surface of the deck and the maximum impact pressure P_{imax}, and the wave uplift foces distribution pattern. According to the results of the model test, provisions can be as the following:

(1) When calculating the wave uplift forces under bridge deck, it is allowed to use the original incident wave elements as the basis;

(2) Waveform is second order finite amplitude wave.

(3) Calculate the hydrostatic buoyancy of bridge deck with the original waveform, then pursue the pressure response coefficient, the results will be the required wave uplift pressure.

In practical engineering design, when the waveform is known, the pressure of wave uplift forces acting on the bottom of the bridge deck can be calculated in the following equation [11].

(2) $$p = \beta\gamma(\eta - \Delta h)$$

where: Δh – the highness from still water surface to the bottom of the bridge, β – a Coefficient of pressure. When the length of the panel along the wave propagation direction less than 10 m,then β =1.5, if the panel width is a bit greater or bank slope is connected with the panel, β =2.0, η – the highness of waveform above still water surface, x – the horizontal distance from wave crest, d – depth of water.

The wave horizontal forces on the bridge

The horizontal force on the bridge panel includes hydrostatic pressure and hydrodynamic pressure. There is no hydrostatic pressure in the wave surface, but on the still water surface.

(3) $$F_{xs} = \gamma\eta$$

Hydrodynamic pressure is,

(4) $$F_{xd} = 1.7\frac{\gamma}{2g}v_x^{\,2}$$

where: v_x – Orbital motion of water particles of the horizontal velocity.

Orbital motion of water particles of the horizontal velocity on the wave crest is,

(5) $$v_x = \frac{\pi d}{T}\frac{\mathrm{ch}(2\pi d(d-z)/L)}{\mathrm{sh}(2\pi d/L)}\cos\frac{2\pi x}{L}$$

For safety, reversed compression on the back of the construction member is ignored. And for each construction member, lateral compression reaches maximum when the crest is forcing on it.

Simulation by 2d numerical wave tank

It uses the 2D numerical wave tank based on the software ANSYS FLUENT which is established to carry on the numerical simulation to various models, and compares with the corresponding experimental values.

Model building

Considering the situation that waves impulse the superstructures of the bridge, it is only studied the superstructures of the bridge between two bridge piers and simplified to plane model. In the pre-treatment module GAMBIT of FLUENT, it establishes geometry two-dimensional model according to actual size of the beam of the double amplitude box bridge. The prototype scale could avoid the scale effect that may influence the result [13, 14], Considering the different situations such as the design water level, wave height, the velocity of flow as well as the bridge elevation and so on, it establishes 18 kinds of models in the different working conditions according to the test data. Concrete models are shown in Fig. 2 and the working conditions of all models are shown in Table 2. The built model is placed in the 2D numerical wave tank. As there are accessory structures on the bridge beam and its shape is complex and irregular, so it simplified here according to the beam shape, not considering the cross slope of the bridge deck and railings, sidewalks and other factors.

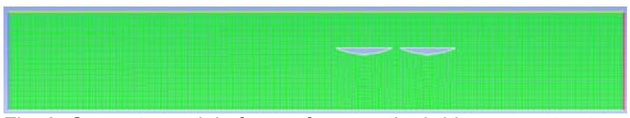


Fig. 2. Compute model of wave force on the bridge superstructure

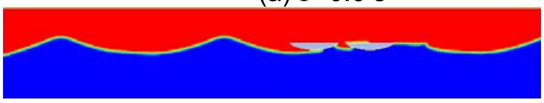
Computation process

In the paper, FLUNET VOF model, Segregated, standard k-ε model, and the PIOS algorithm of pressure-velocity coupling method are adopted to solve the unsteady turbulent flowing [14]. The wall boundary conditions are applied to the bottom, while the pressure boundary conditions are to the upper. Fig. 3 and Fig. 4 are respectively (bridge elevation + 6.0 m, seabed elevation -10 m, design level + 4.33 m, $H_{1\%}$=3.58 m, T=5.6 s) the process of interacting between the wave and the bridge superstructure of Model M2 in the flow velocity of 1.5 m/s, the distribution charts of hydrosphere particle velocity, and the monitor figure of lift and drag coefficient of the first beam. The duration of 3~5 cycles are calculated in order to find out the maximum force.

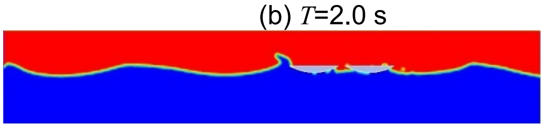
Table 2. Condition of compute model of wave force on the bridge superstructure

Model NO.	BE [m]	Design water level [m]	Wave direction	Wave factor	SBE [m]
M1	+5.5	+4.33	S	$H_{1\%}$= 3.58 m T=5.6 s	-10.0
M2	+6.0				
M3	+6.5				
M4	+7.0				
M5	+5.5	+3.16		$H_{1\%}$= 3.44m T=5.6s	
M6	+6.0				
M7	+6.5				
M8	+5.5	+4.33		$H_{1\%}$= 3.58m T=5.6s	-4.0
M9	+6.0				
M10	+6.5				
M11	+7.0				
M12	+5.5	+3.16		$H_{1\%}$= 3.44m T=5.6s	
M13	+6.0				
M14	+6.5				

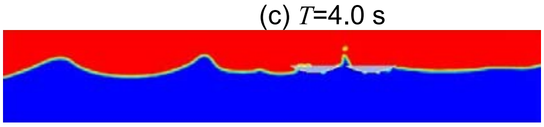
(a) T=0.6 s



(b) T=2.0 s



(c) T=4.0 s



(d) T=11.0 s

Fig. 3. Process of interacting between the wave and the bridge superstructure of Model M2

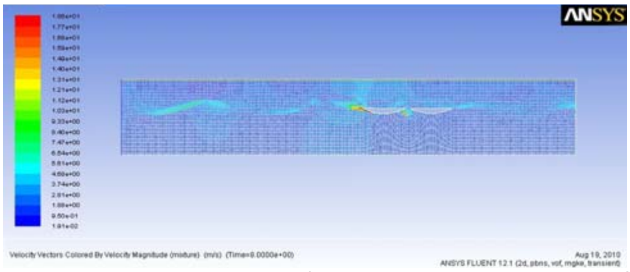
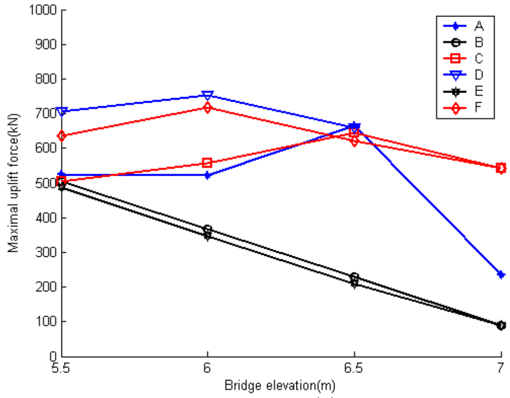


Fig. 4. The distribution charts of hydrosphere particle velocity of Model M2

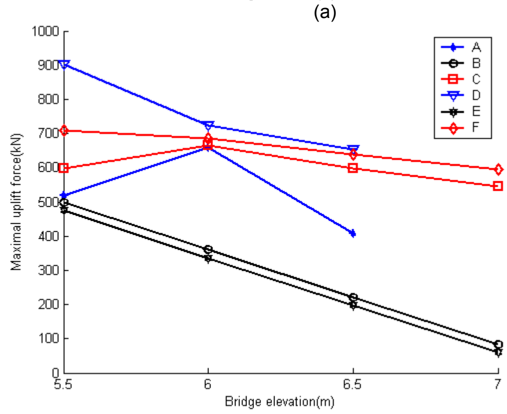
Comparison and analysis

In order to compare conveniently, load values are directly compared and analyzed in the paper. From the following contrast charts, it can be seen that the bridge elevation and the design water level have a great effect on the maximal vertical uplift force and the maximal horizontal force to the bridge superstructure.

The test measured values, the theoretical calculation values and the numerical simulating values of the maximal vertical uplift force and the maximal horizontal force on the bridge superstructure are compared in the same coordinate system. The experimental values are based on the references [3, 5].

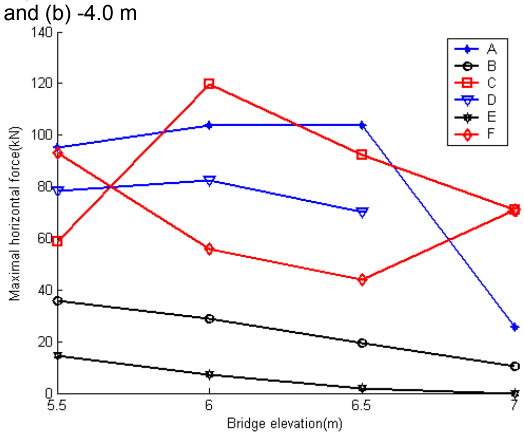


(a)

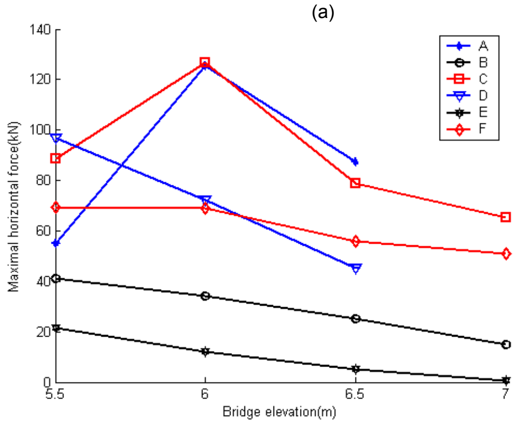


(b)

Fig. 5. Maximal uplift force of different elevation of sea bed (a) -10.0 and (b) -4.0 m



(a)



(b)

Fig. 6. Maximal horizontal force of different elevation of sea bed (a) -10.0 and (b) -4.0 m

Note: In Fig. 5 and Fig. 6, “A”, “B”, “C” are the numerical simulation results, the theoretical calculation values and the experimental values of the conditions (design level +4.33 m, $H_{1\%}$=3.58 m, T=5.6 s), “D”, “E”, “F” are the numerical simulation results , the theoretical calculation values and the experimental values of the conditions (design level +3.16 m, $H_{1\%}$=3.44 m, T=5.6 s).

With the raised of the elevation of the bridge deck, the values of the maximal vertical uplift force and the maximal horizontal force on the bridge superstructure are gradually reduced, which can be seen from the result comparison in Fig. 5 and Fig. 6. The reason is as the lift of the deck elevation, the contact area that wave crest on the underside bridge decrease.

Except some points of the numerical calculating values, the theoretical calculation values and the experimental test values of the maximal vertical uplift force and the maximal horizontal force, it's basically tallies in a number magnitude scope. On the whole, however, the numerical calculating values are bigger than the experimental test values slightly. The reason that causes the result is mainly because partial test results calculated by minusing the test value of negative pressure in considering the influence of negative vertical pressure when carried out the test.

On the same bridge elevation, the numerical calculation values and test values of the maximum vertical uplift force at water level +3.16 and $H_{1\%}$=3.44 m are larger than that at water level +4.33 and $H_{1\%}$=3.58 m; and the numerical calculation values and test values of maximal horizontal force at water level +3.16 and $H_{1\%}$=3.44 m are smaller than that at water level +4.33 and $H_{1\%}$=3.58 m. So the maximum vertical uplift force does not increase as the addition of the significant wave height but depends on the elevation of still level.

Owing to the test values and numerical calculation values are the maximum in a certain period and the force is affected by the comprehensive influence of many external factors, so the variation of all the forces is not consistent with the addition of bridge elevation. However, all the forces are basically declined from the overall values. The theoretical calculation values are basically linear down trend, and the calculated values under two wave conditions have not significant differences. The experiment test values and the numerical calculation values are far greater than the theoretical calculation values in Fig. 5 and Fig. 6. The reason of this phenomenon is that the maximum wave forces are both collected, that is considered the slamming force of wave, but the theoretical calculation values are not considered its action. Therefore, there are some risks that the theoretical calculation method applied directly on wave force calculation of bridge girder.

Conclusions

(1) All the forces are descending with the increase of bridge elevation. The optimum deck height is +5.5~ +6.0 m according to comparison and analysis on the wave forces.

(2) The analysis results show that the bridge girder form is beneficial to alleviate the wave action, and it is feasible that bridge elevation is +5.5~+6.0 m. It not only reduced the engineering investment and took into account the landscape effect, but also avoided the visual pollution of the tourists.

(3) Form the test data, theoretical calculation values and numerical calculation values, the maximum vertical uplift force and the maximal horizontal force will reach maximum within the range of +6.0~+6.5 m of bridge elevation, then become declined. Therefore the most dangerous bridge elevation under wave action exists in bridge design, so it should be avoided. But to find the discipline of the most dangerous bridge elevation, a lot of experimental and numerical simulation works of different types of bridges, which combined with sea condition and wave condition, need to be done.

Acknowledgment: *This work is financially supported by China National Science Foundation (50878145), Shandong Province Higher Educational Science and Technology Program (J10LE11, J11LE10), the Project of Qingdao Construction Technology Program (JK10-3), to which the authors gratefully appreciate.*

REFERENCES

1. Weggel J. R., *Journal of Waterway, Port, Coastal and Ocean Engineering*, 123(1997), 143-146
2. Bea R. G., Iversen R and Xu T., *Journal of Offshore Mechanics and Artic Engineering*, 123(2001), 10-21
3. Xiao X. L., *Technology of Highway and Transpor*t, (2001), No.1, 76-79 (in Chinese)
4. Zhang X. T., Chen A.R., Wang C. and Gao K. N., *Advanced Materials Research*, 163-167(2011), 4083-4087
5. Tong D. S., Xie S. W., Pang T. Z and Yang X. B., *China Harbour Engineering*, 6 (2003), 41-44(in Chinese)
6. Chen Q., Zhao H., Hu K. and Douglass S. L., *Journal of Waterway, Port, Coastal and Ocean Engineering*, 131 (2005), No. 4, 137-148
7. Douglass S. L., Chen Q. J., Olsen J. M., Edge B. L. and Brown D., *U.S. Department of Transportation Federal Highway Administration Office of Bridge Technology Washington, DC* (2006)
8. Li S. Z, *Harbin Institute of Technology*, Harbin (2006) (in Chinese)
9. Cuomo G., Shimosako K. I. and Takahashi S., *Coastal Engineering*, 56(2009), 793-809
10. Zhang X. T. and Chen A. R., *in International symposium on life-cycle performance of bridges and structures, Edited J. R. Zhang and C. S. Cai,* Science Press, Beijing (2010), 972-977
11. The First Harbour Engineering Investigation and Design Institute of the Ministry of Communications, *Handbook for design of sea Harbours*, China Communications Press, Beijing (2001) (in Chinese)
12. Ministry of Transport of the PRC, *Wave model test regulation*, JTJ/T 234-2001, China Communications Press, Beijing (2002) (in Chinese)
13. Zhang C. H., *Analysis on ANSYS 12.0 Engineering Application Example of Structural Analysis*, China Machine Press, Beijing (2010) (in Chinese)
14. Fluent Inc, *FLUENT 6.2 User's Guide*, (2005)

***Authors**: associate prof. dr Xiantang Zhang, The College of Civil Engineering and Architecture ,Shandong University of Science and Technology, Qianwan port road 579,E-mail: zzxhtm@163.com; lecturer Hongmin Zhou, E-mail: hongminzhou@163.com; associate prof. Hongli Wang, E-mail: skdwhl@163.com; Master graduate student Kangning Gao, E-mail: gkngkn@163.com.*

The correspondence address is: e-mail: *zzxhtm@163.com*